Convective hydration in the tropical tropopause layer during the StratoClim aircraft campaign: Pathway of an observed hydration patch

By K. O. Lee et al.

Reply to the referees' comments

In the following, the comments made by the referees appear in black, while our replies are in red, and the proposed modified text in the typescript is in blue.

Referee #3 comments

General Comments

This article investigates an observed hydration patch in the area of the Asian Monsoon observed by the StratoClim aircraft campaign. The Meso-NH model is run over several days and accurately simulates the hydration patch and the proceeding convection. The simulation demonstrates the hydration patch can be attributed to convective influence from the days prior to the observation. I think this is an interesting case and the tracking back in time of the hydration patch to see how the atmosphere responds to the convective influence is compelling. However, this article also attempts to describe in more detail the physical and dynamical processes that explain the evolution of the atmospheric environment. I found much of this text to be poorly supported. The specific statements that need more support are listed below. Or the authors could choose to remove some of these statements because they can't be investigated with the current model (or time does not permit investigation). In that case, the authors can submit a revised article that is a much more concise case study of an interesting simulated hydration event.

Additionally, the authors fail to reference several articles on mid-latitude hydration and/or convective transport events that seem relevant for this study. A non-exhaustive list of these articles are included in the comments below.

We appreciate the time and effort you put in this review as well your mindful comments on our paper. We have worked hard to state clearly the processes and to list up-to-date reference articles on mid-latitude hydration and convective transport events. Replies to each comment are listed below.

Comments on Process Statements:

1. The separation between the troposphere and stratosphere is identified as the 380 K level. This is a reasonable definition in the mean, but is an oversimplified definition at convection-allowing scales. I think this study clearly shows deep injection of water vapor by convection, but there should be some discussion of the difficulty of defining a tropopause in convective environment. For example, see:

Maddox, E.M. and G.L. Mullendor, 2018: Determination of Best Tropopause Definition for Convective Transport Studies. J. Atmos. Sci., 75, 3433–3446, https://doi.org/10.1175/JAS-D-18-0032.1

Agreed. There exist several tropopause definitions in various literature (e.g. Maddox and Mullendore, 2018), considering temperature lapse rate, potential vorticity, static stability, and tracer chemicals. As you mentioned, it is true that there is a difficulty of defining a tropopause in convective environment. This has been discussed in the manuscript as below:

♣ From Page 6, lines 171

"[…] There exist several tropopause definitions, considering temperature lapse rate, potential vorticity, and static stability (WMO, 1957; Maddox and Mullendore, 2018). In this study, the overshoots are defined as convective cloud tops that reach the lowermost stratosphere above 380 K level. This simple definition is sufficient enough to study the impact of convective hydration on the TTL as it quickly returns to its undisturbed state (Dauhut et al., 2018)."

2. Using the tropopause definition above, a tropospheric tracer is defined to track mixing between the troposphere and stratosphere. There is the issue discussed above of an oversimplified tropopause definition. But more importantly, this is an odd approach to highlighting moistening from the troposphere. I expect the moisture content of the upper troposphere in this region is much lower than the moisture content of the lower troposphere. The approach used here has no way to distinguish between mixing of lower tropospheric (as transported by deep convection) or upper tropospheric air. Additionally, because the tropospheric air being tracked is right at tropopause level, a lot of the observed mixing may occur due to numerical diffusion, which tends to be stronger than true atmospheric diffusion. (And even if the numerical diffusion is physical, may track mixing of air parcels that are not very different in terms of water vapor content). This issue can be seen in Figure 8 with the strong gradient that forms at all locations over time, which just looks like diffusion. It would be instructive to show what the tropospheric tracers looks like away from convective events to assess what portion of the vertical mixing is convectively enhanced and what portion is just diffusion. Figure 11 is not compelling. Finally I don't know of any tropospheric chemical tracer that looks like that (Figure 8) across the tropopause.
Note: I do agree that the mixing is enhanced around the time of convection, but it's not clear if the mixing is of significantly different air masses, or just enhancing the diffusive processes in the vicinity of convection. Again, this problem is due to that fact that you don't know where in the troposphere this air is from. Many articles have used tracers to study deep convective transport, but are able to better distinguish source. For example:

Homeyer, C.R. (2015), Numerical simulations of extratropical tropopause–penetrating convection: Sensitivities to grid resolution. J. Geophys. Res. Atmos., 120, 7174–7188. Doi: 10.1002/2015JD023356
Mullendor, G.L., D.R. Durran, and J.R. Holton (2005), Cross-Tropopause tracer transport in midlatitude convection, J. Geophys. Res., 110, D06113, doi:10.1029/2004JD005059

We agree that the tracer employed in this study is simplistic to find out the sophisticated origin of the air mass. In this study, however the purpose of the tropospheric tracer is to see the mixture of tropospheric air and stratospheric air in the layer above 380 K isentropic altitudes. And this simple set up is able to show the changes of the concentration of tropospheric air. For the sake of clarity, Figure 8 has been improved by removing the wind vectors and changing the unit to percentage ranging from 0 to 100, while the main changes of the tropospheric tracer within the convective overshoots are pointed by arrows. During 13:00–23:00 UTC on 6 August, the concentration of tropospheric air increases, e.g. from 0 up to about 50 % around 103°E (Fig. 8a–f).

At the same time, as you pointed out, there is limitation of this simple set up to distinguish i) the numerical diffusion by the sharp gradients, and ii) the origins of air parcels coming from lower, middle or upper tropospheric air. For this, additional analyses using further setup (e.g. Mullendore et al., 2005; Hassim and Lane, 2010; Homeyer, 2015; Dauhut et al., 2016) is required. This limitation has been discussed in the manuscript.

♣ From Page 16, lines 459

"The simple set up of tropospheric tracer of this study, i.e. tropospheric air below the 380 K isentropic altitude, allows to understand the mixture of tropospheric and stratospheric air parcels in the TTL by vigorous convective overshoots. To estimate the detailed origin i.e. defining the lower, middle, and upper troposphere, of air parcel, further sophisticated analyses (e.g. Mullendore et al., 2005; Hassim and Lane, 2010; Homeyer, 2015; Dauhut et al., 2016) will be required."

♣ Reference list

Homeyer, C. R.: Numerical simulations of extratropical tropopause penetrating convection, J. Geophys. Res. Atmos., 120, 7174–7188. doi: 10.1002/2015JD023356, 2015.

Hassim, M. E. E. and Lane, T. P.: A model study on the influence of overshooting convection on TTL water vapour, Atmos. Chem. Phys., 10, 9833–9849, https://doi.org/10.5149/acp-10-9833-2010, 2010

Mullendore, G. L., Durran, D. R., and Holton, J. R.: Cross-Tropopause tracer transport in midlatitude convection, J. Geophys. Res., 110, D06113, doi:10.1029/2004JD005059, 2005.

♣ Page 29

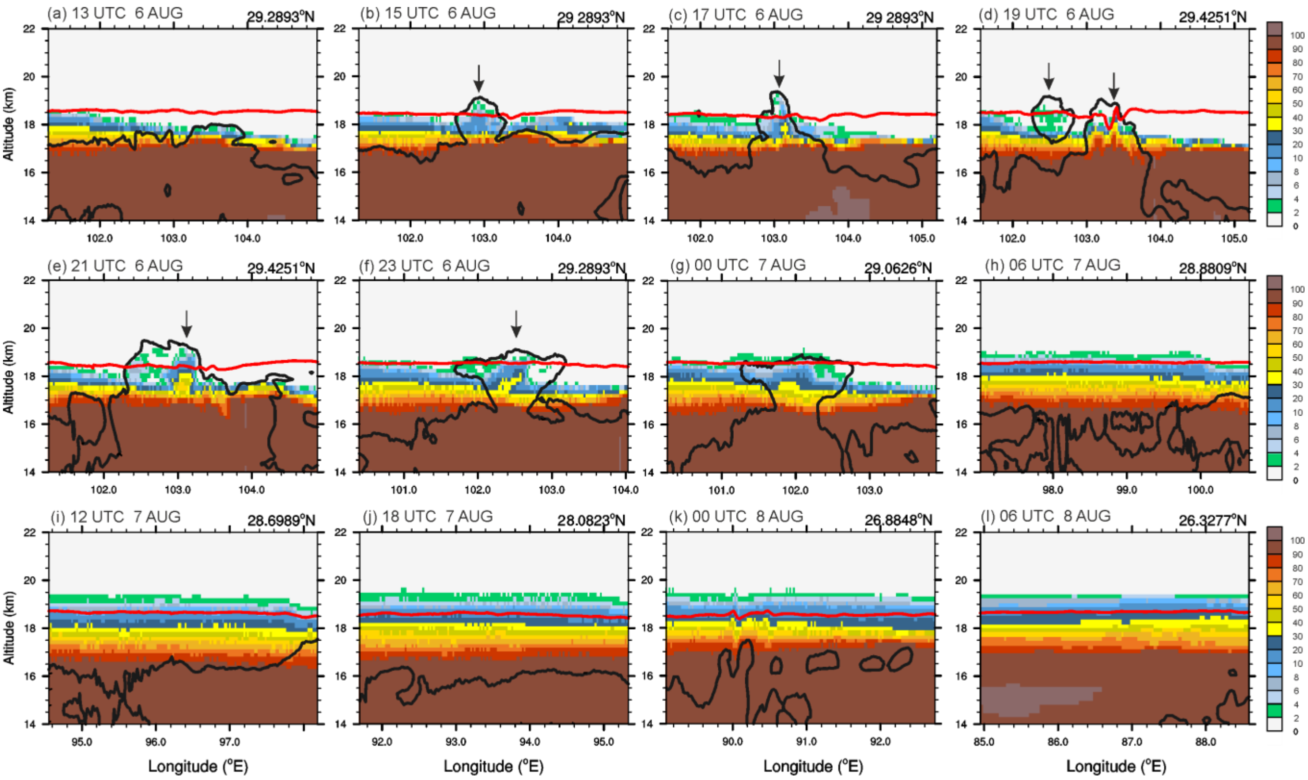

Figure 8. Same as Fig. 7 but for the tracer (%). The isentropic altitude of 410 K is depicted by the red line. The main changes of the tropospheric tracer by convective overshoots is marked by downward arrows.

3. The definition of ML and IL is based on height ranges. Line 294 states that "the temperature increases in both layers, indicating the mixing with the warmer stratospheric air". As shown in Maddox and Mullendore (2018; reference above), during the convective event, the tropopause cannot be reliably defined, but we at least know that the tropopause surface is pushed upward during the event. "Mixing with stratospheric air" doesn't make sense here. If you are showing the influence of overshoots only, which are colder than the surrounding air, the layer temperature will go down. You may instead be seeing the tropospheric column heating occurring due to the convection (e.g. see comment in Maddox and Mullendore, p. 3438). Or this may be due to local heating due to ice particle formation.

It is true that the strong updraughts of overshooting convective system perturb the tropopause layer, injecting a large amount of tropospheric moisture across the tropopause. During the collapse of the overshooting top, the stratospheric dry and warm air can flow in. The conditions and timescale of the detailed process trapping the enriched vapour in the TTL was demonstrated in Dauhut et al. (2018). Thanks to a fine temporal resolution of 1 min, they reveal that this process occurs shortly within 20 min. The warm, sub-saturated stratospheric air causes the ice to rapidly sublimate into water vapour at the top of the overshoot, moistening the layer. It is thus that both intrusion of stratospheric air by the overshooting convection and activated ice microphysics derives the increase of temperature in ML and IL. This discussion has been stated in the manuscript.

♣ From Page 9, lines 253

"At 17:00 UTC even higher cloud top is apparent at ~19.5 km altitude (Fig. 6c), a large amount of water vapour (≥ 18 ppmv) rises to ~20 km, around 103°E, and a large ice content (≥ 120 eq. ppmv) stays below 18 km altitude (Fig. 7c). The large amount of water is directly injected by convective overshoots mainly in the form of ice, as the air within the overshooting of the ice-laden air with the entrained stratospheric air during the collapse of the overshooting top. The warm, sub-saturated stratospheric air causes the ice to rapidly sublimate into water vapour at the top of the overshoot, moistening the layer. It is worth noting the water injected by the convective overshoots at 15:00 UTC is still apparent in ML at 17:00 UTC around 102°E with a water vapour mixing ratio above 9 ppmv (Fig. 6c). In a similar way, the convectively-injected large moisture at 17:00 UTC around 103°E (Fig. 6c) is found in ML at 19:00 UTC around 102.5°E with a water vapour mixing ratio larger than 15 ppmv (Fig. 6d)."

♣ Page 11, lines 301–311

"[…] During the development of the convective overshoots between 14:00 and 21:00 UTC on 6 August 2017, the average water vapour mixing ratio increases to 5.7 ppmv in IL (yellow solid line, Fig. 10a), while a large mixing ratio of 6.5 ppmv is seen in ML (blue solid line in Fig. 10a). The ice content reaches more than 200 eq. ppmv in both layers even more than 300 eq. ppmv in IL (Fig. 10b). Until 17:00 UTC, the temperature increases in both layers (solid lines in Fig. 10c), indicating the mixing with the warmer stratospheric air. Because of this entrained stratospheric air, RH_{ice} decreases largely below 60 % in ML (blue line with symbols in Fig. 10c), and down to 90 % in IL (yellow line with symbols). Due to the mixing with entrained warmer stratospheric air, the enriched vapour layer then remains at this higher isentropic level after the overshoot collapses. The conditions and timescale of the detailed process trapping the enriched water vapour in the TTL was demonstrated in Dauhut et al. (2018). Thanks to a fine temporal resolution of 1 min, they revealed that this process occurs shortly within 20 min."

4. Mixing pathways are not investigated sufficiently in this article to accept Figure 12 as a proven mechanistic diagram. The authors state several times that gravity waves are likely an important, but don't do any investigation into gravity wave overturning. At the resolution of this model, you should be able to observe steep isentropes in the vicinity of the overshoot that indicate gravity wave breaking. And I have detailed other concerns about the amount of mixing from diffusion above. I don't dispute that convection has played an important role in the observed hydration, and the article can still be published as an important case study. But Figure 12 is an overreach based on the analyses done here. I think it should be removed.

Agreed. To better understand about the process along the pathway of hydration patch, we have investigated the evolution of ice particles. In Figure 11e, the ice content (solid lines) and cloud ice (dashed lines) are separately displayed (previously Figure 10). The latter shows that IL includes much reduced amount of ice content than the previous time (green to blue solid lines), but still there is ice content ≥ 1 eq. ppmv and cloud ice ≥ 0.5 eq. ppmv at 12:00 UTC on 7 August (blue dashed line). Meanwhile, the turbulent kinetic energy (TKE) largely increases from 0.1 to 0.3 $m^2\ s^{-2}$ in both ML and IL (Fig. 9). Thus we conclude that the turbulent diffusion is the main source for dehydrating ML and IL, but it is not the sole cause. The vapour-scavenging effect plays a role in decreasing the water vapour amount. The manuscript has been improved by including this point. For the sake of clarity, the vertical cross-sections of TKE from 13:00 UTC on 6 August to 06:00 UTC on 8 August have been joined as Figure 9 in the manuscript and further details about TKE and ice microphysics have been included. Considering these, the schematic illustration has been improved.

♣ Page 10, line 268–270

"[…] During 17:00–21:00 UTC (Fig. 9c–e), the large turbulent kinetic energy (TKE) of 0.2–0.9 m^2 s^{-2} is apparent in a limited area of cloud top (~103°E)."

♣ Page 10, line 276–277

"[…] Within the anvil cloud, still large TKE of 0.2–0.9 m^2 s^{-2} is seen (Fig. 9f, g)."

♣ Page 10, line 283–285

"[…] The air mass with high tropospheric tracer concentration of 2–40 % consistently exists in ML and IL from 00:00 to 06:00 UTC on 8 August 2017 (Fig. 8k–l), while the TKE of 0.2–0.9 m^2 s^{-2} exists in wide area between the altitudes of 16 and 18 km (Fig. 9k–l)."

♣ Page 13, lines 352–358

"This can be also seen in the vertical profiles for which the concentration of tropospheric tracer increases at 12:00 UTC on 7 August in both ML and IL (green to blue lines, Fig. 11a) and the water vapour decreases (green to blue lines, Fig. 11d). The two layers become colder by ~3°C (green to blue lines in Fig. 11b), and dehydrated compared to the initial state of 13:00 UTC on 6 August (yellow line in Fig. 11d, e). It includes much reduced amount of ice content (green to blue solid lines in Fig. 11e), but still there exist ice content ≥ 1 eq. ppmv and cloud ice ≥ 0.5 eq. ppmv at 12:00 UTC on 7 August (blue dashed line, Fig. 11e)."

♣ Page 13, lines 364–365

"Also, the vapour-scavenging effect by ice nucleation and growth within IL contributes to reduce the water vapour deriving the dehydration."

♣ Page 13, line 360–362

"[…] Moreover, the turbulent kinetic energy (TKE) increases from 0.1–0.3 m^2 s^{-2} at 21:00 UTC to 0.2–0.9 m^2 s^{-2} at 12:00 UTC in ML and IL (~~not shown~~Fig. 9e, i)."

♣ Page 14, line 391–392

"[…] The air mass in ML and IL has large TKE values of 0.5 m^2 s^{-2} (~~not shown~~Fig. 9l)."

♣ Page 30

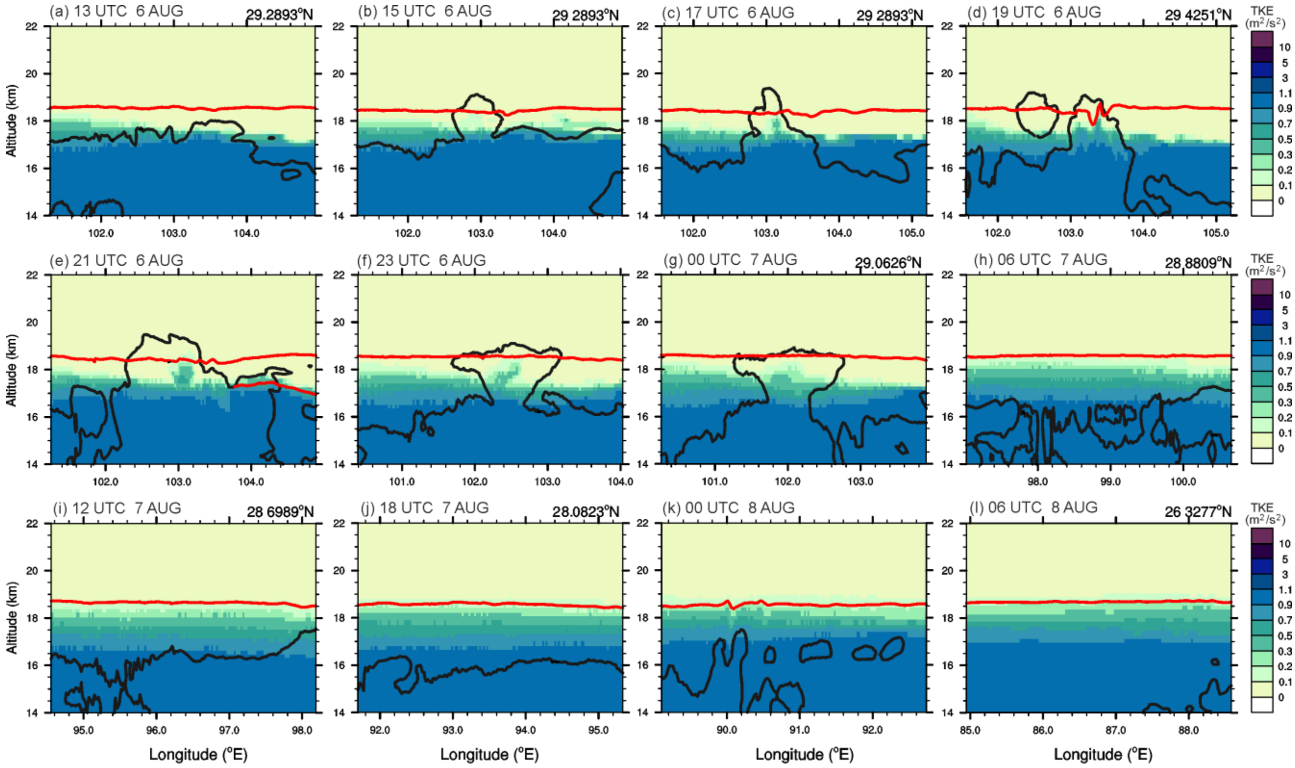

Figure 9. Same as Fig. 6 but for the TKE. The isentropic altitude of 410 K is depicted by the red line.

♣ Page 32

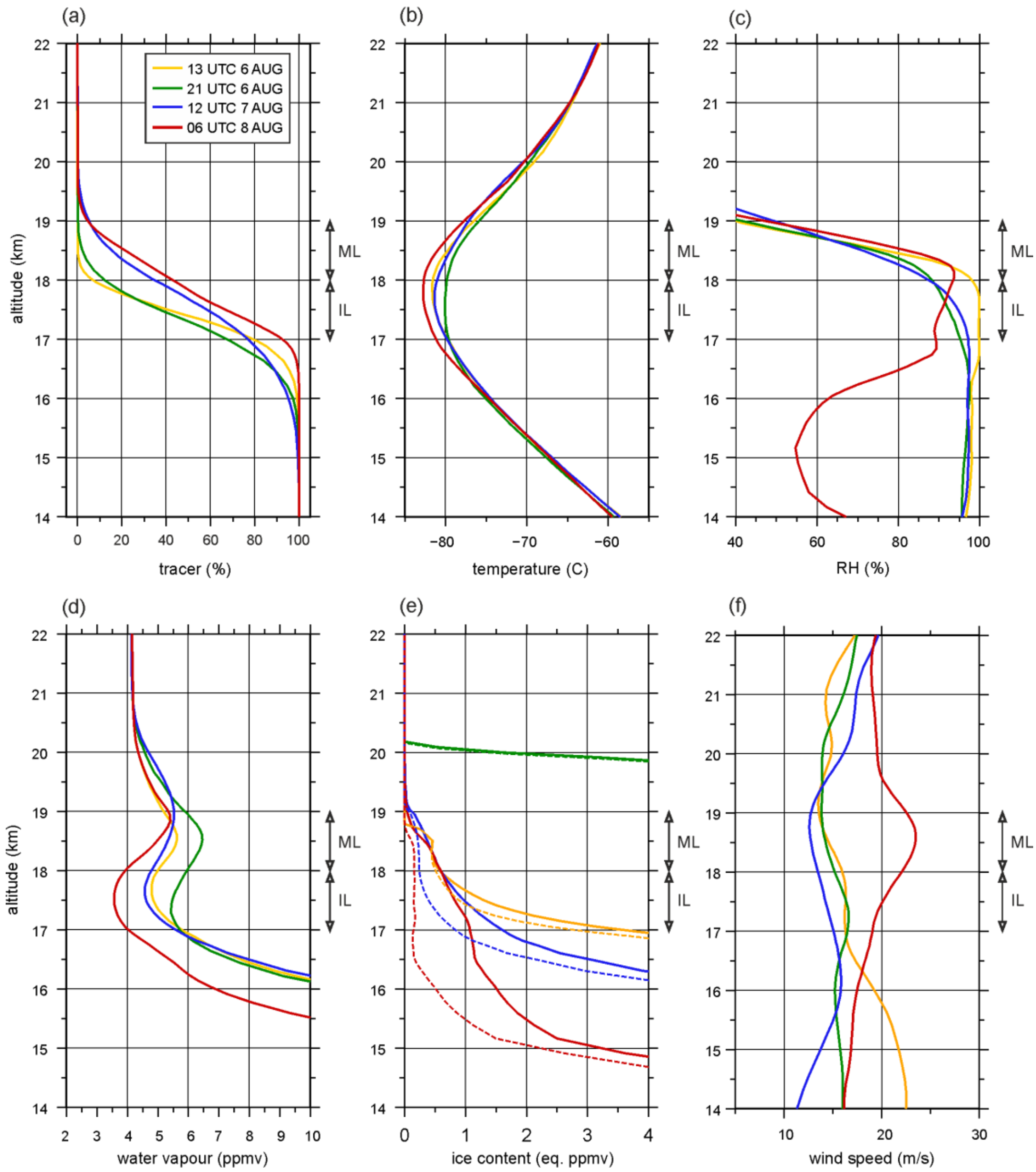

Figure 11. Vertical profiles of (a) tracer (%), (b) temperature (°C), (c) relative humidity (%), mixing ratios of (d) water vapour (ppmv), (e) ice content (eq. ppmv), and (f) wind speed (m s^{-1}) across the hydration patch along the trajectory at 13:00 UTC (yellow line), 21:00 UTC (green line) on 6 August, 12:00 UTC on 7 August (blue line), and 06:00 UTC (red line) on 8 August 2017. The layers of ML and IL are marked by arrows. In (e), the ice content is depicted by solid lines, while the cloud ice are shown by dashed lines.

♣ Page 34

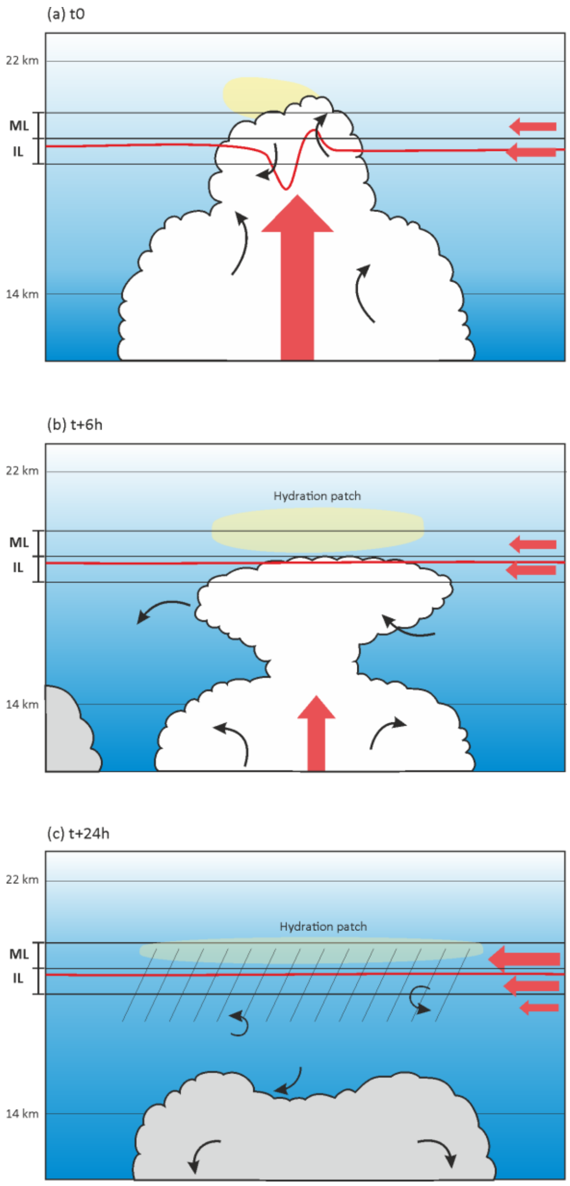

Figure 13. Schematic illustration summarising the hydration process in the TTL during flight #7 of the StratoClim 2017 field campaign. (a) Mixing of the overshoots with the stratospheric air, (b) and (c) turbulent mixing of the hydration patch with the tropospheric air by vertical wind shear. The bottom and top of the TTL, 14 and 22 km, and the moist layer (ML) and ice layer (IL) are represented by the black solid line, and the 410 K isentropic altitude is represented by the red solid line. The main force in the TTL is marked by bold red arrows, while the turbulent eddies in/around the developed and weakened overshoots are described by black arrows. The overreaching water vapour above the cloud top level is indicated by a yellow ellipsoid in (a). The hydration patch is yellow-encapsulated in (a) and (b), and the layer of dehydration by turbulent diffusion and ice microphysics is hatched in (c). The blue shades illustrate the concentration of tropospheric air, showing the increased tropospheric air in the TTL by the turbulent mixing in (b) and (c).

5. besides sensitivity to the turbulent mixing parameterization in this model, and possibly to the numerical diffusion (separate from turbulence parameterizations), other numerical sensitivities may be in play and are not discussed. The most significant of these is the sensitivity to the microphysical parameterization, which could have a significant impact on the hydration processes discussed.

Absolutely. Even our simulation results are reasonable comparing to the observational features, it is true that still some sensitivities of the results to parameterizations, especially the microphysical scheme, should exist. In this study, we used a 1-moment bulk microphysical scheme (Pinty and Jabouille, 1988), which governs the equations of six water categories (water vapour, cloud water, rain water, pristine ice, snow and graupel). For each particle type, the sizes follow a generalized Gamma distribution while power-law relationships allows the mass and fall speed to be linked to the diameters. In a future study, conducting a simulation with a 2-moment microphysical scheme that considers the mass and number concentration of hydrometeors, as well concentration of aerosols, would be worthwhile. This point has been included in the manuscript.

♣ Page 17, lines 464–467

"[…] Also, additional numerical simulations with a 2-moment microphysical scheme that considers mass and number concentration of hydrometeors and aerosol together with options in the turbulent scheme (e.g., 1D against 3D formulations, Machado and Chaboureau, 2015) will be worthwhile to study the impact on the results."

Machado, L. A. and Chaboureau, J. P.: Effect of Turbulence Parameterization on Assessment of Cloud Organization. Mon. Wea. Rev., 143, 3246–3262, https://doi.org/10.1175/MWR-D-14-00393.1, 2015.

Additional comments

Line 35: "…Middle East and is located on the edge…"

Corrected.

Line 43: "…relatively high at about 4.2 ppmv…"

Corrected.

Line 56: "The most energetic one forms…" Energetic what? I assume you mean convective core, but this phrasing is clunky.

It has been rephrased to "They eventually form…".

Line 59: I realize your list of prior studies analyzing water vapor injection by convective overshoots is not meant to a complete list, but some recent articles are missing from your list and I want to make sure you have incorporated their findings into your assessment:

1. Homeyer, C.R., et al. (2014), Convective transport of water vapor into the lower stratosphere observed during double- tropopause events, J. Geophys. Res. Atmos., 119, 10, 941–10,958, doi:10.1002/2014JD201485.
2. Homeyer, C.R., J.D. McAuliffe, and K.M. Bedka, 2017: On the development of above-anvil cirrus plumes in Extratropical convection. J. Atmos. Sci., 74, 1617–1633, https://doi.org/10.1175/JAS-D-16-0269.1

Thank you for listing the recent articles. These have been cited in the manuscript as well as two other mid-latitude studies, but over Europe.

Funatsu, B. M., Rysman, J. F., Claud, C., and Chaboureau, J. P.: Deep convective clouds distribution over the Mediterranean region from AMSU-B/MHS observations, Atmos. Res., 207, 122−135, https://doi.org/10.1016/j.atmosres.2018.03.003, 2018.
Rysman, J.-F., Claud, C., Chaboureau, J. P., Delanoë, J. and Funatsu, B. M.: Severe convection in the Mediterranean from microwave observations and a convection-permitting model, Quart. J. Roy. Meteor. Soc., 142, 43−55, https://doi.org/10.1002/qj.2611, 2016.

Line 79: "…that was measured by aircraft in connection to a convective overshoot."
Corrected.

Line 80: "…and spaceborne observations as well as…"
Corrected.

Line 160: The hydration patch is "chased" back in time: You need to include a more quantitative explanation of exactly how the location of the hydration patch was identified going back in time.
For the sake of the clarity, the description about the hydration patch has been further improved in the manuscript.

♣ Page 6, lines 160–164
"[…] The hydration patch is chased visually back in time every hour from 06:00 UTC on 8 August to 13:00 UTC on 6 August 2017, considering the prevailing wind direction and speed at 410 K isentropic altitude. At 14:00 UTC, a large amount of water vapour (≥ 6.6 ppmv), that is injected by the convective overshoot in the Sichuan basin, starts to appear at this altitude, generating a hydration patch. With the dominant east-northeasterlies (15–20 m s^{-1}), it travels to the south of Kathmandu."

Also, Figure 4 has been improved joining the horizontal wind at the altitude of 19 km (nearly equivalent to 410 K isentrope) at 06:00 UTC on 8 August. The dominant wind is east-northeasterlies at the speed of 15–20 m s^{-1}. The wind direction corresponds to the pathway of the hydration patch from the Sichuan basin at 14:00 UTC on 6 August (Fig. 4e) to the south of Kathmandu at 06:00 UTC on 8 August (Fig. 4a). During 14:00–21:00 UTC on 6 August, the hydration patch moved westward with weak easterly wind (about 10 m s^{-1}). Then during 00:00–06:00 UTC on 8 August, the hydration patch moved farther southwest, to the south of Kathmandu with the strong east-northeasterlies (about 25 m s^{-1}).

♣ Page 26

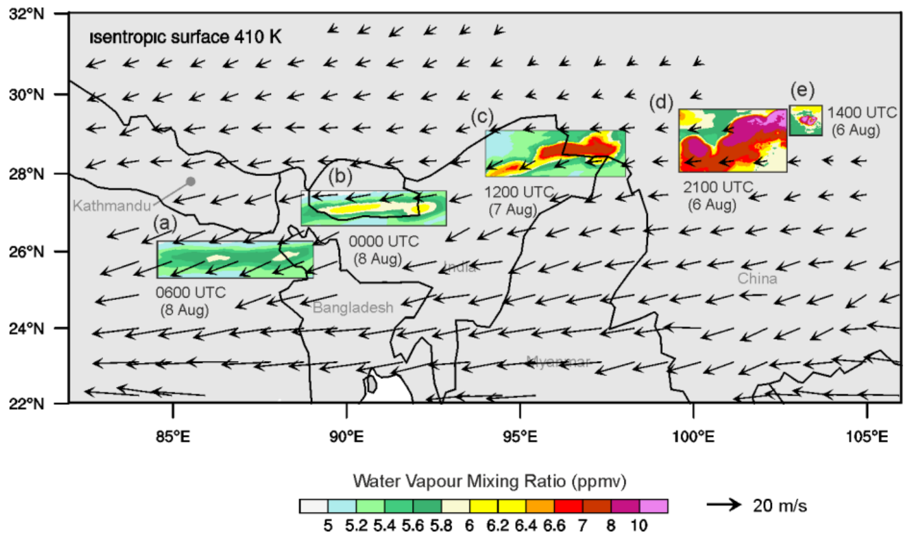

Figure 4. Target moist patch. Horizontal distribution of water vapour mixing ratio at 410 K isentropic altitude at (a) 06:00 UTC, and (b) 00:00 UTC on 8 August, (c) 12:00 UTC on 7 August, (d) 21:00 UTC and (e) 14:00 UTC on 6 August 2017. The horizontal wind at the altitude of 19 km (about 410 K isentrope) at 06:00 UTC on 8 August is displayed by vectors.

Line 223-225: Looking at Figure 5, there do seem to be some isolate overshoots at 13 UTC, as there are some areas of very cold brightness temperatures.
Corrected.

Figures 6, 7, and 8: The small black lines are not labelled, but they look like wind vectors. These should be removed because they are not discussed, and they make these plots hard to read.
For the sake of readability, the wind vectors in Figures 7 and 8 are removed while remaining in Figure 6 to show the updraughts in the overshooting convection. Figure 6 has been revised by changing the colour of cloud boundary to white and the wind has been stated in the manuscript.

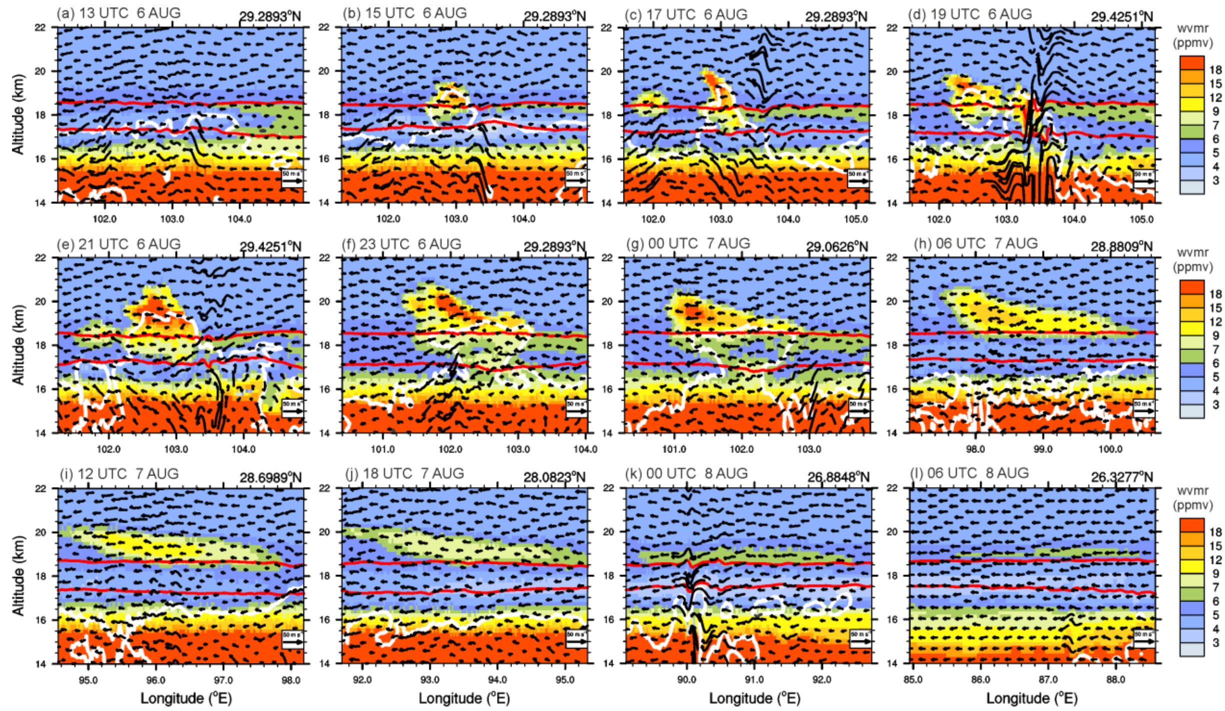

Figure 6. Vertical cross-sections of water vapour mixing ratio (shading) and wind (vectors) (a) 13:00 UTC, (b) 15:00 UTC, (c) 17:00 UTC, (d) 19:00 UTC, (e) 21:00 UTC, (f) 23:00 UTC on 6 August 2017, (g) 00:00 UTC, (h) 06:00 UTC, (i) 12:00 UTC, (j) 18:00 UTC on 7 August 2017, and (k) 00:00 UTC and (l) 06:00 UTC on 8 August 2017. The isentropic altitudes of 380 and 410 K are depicted by the red lines. The latitude (°N) of west-east oriented cross-section line is indicated at the upper right of each panel. The cloud boundary (mixing ratio of ice content of 10 mg kg^{-1}) is contoured by the white solid line.

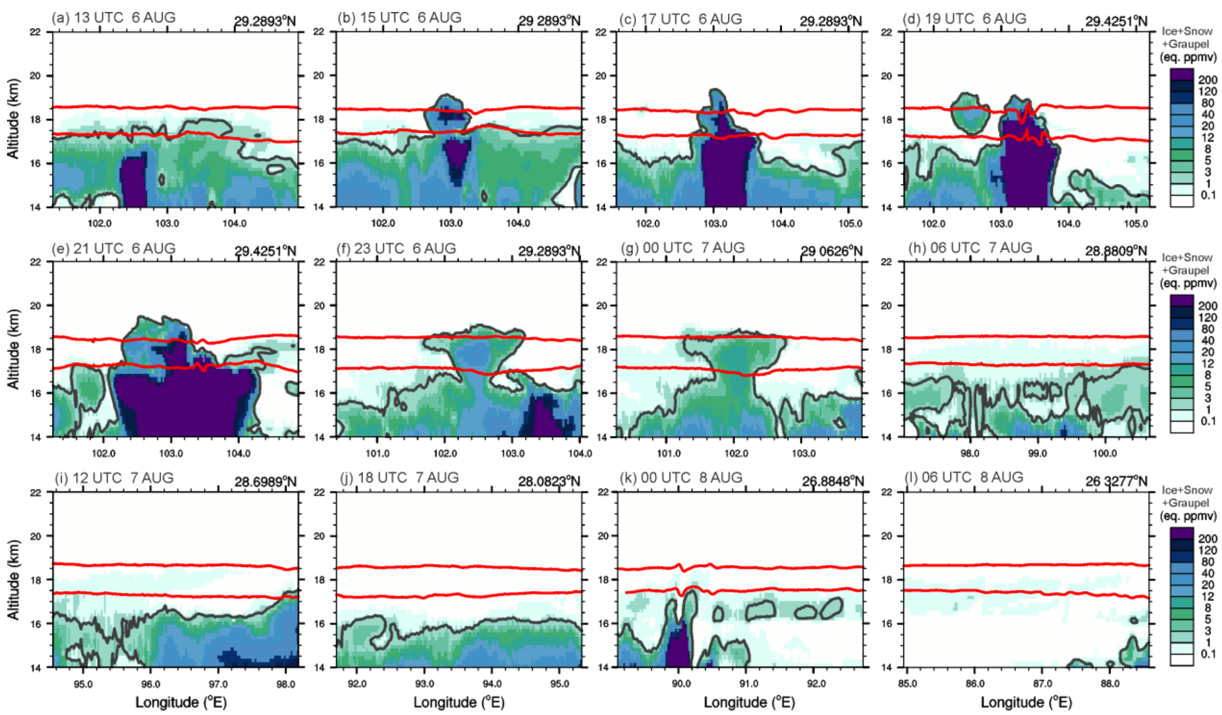

Figure 7. Same as Fig. 6 but for the ice content. The isentropic altitudes of 380 and 410 K are depicted by the red lines.

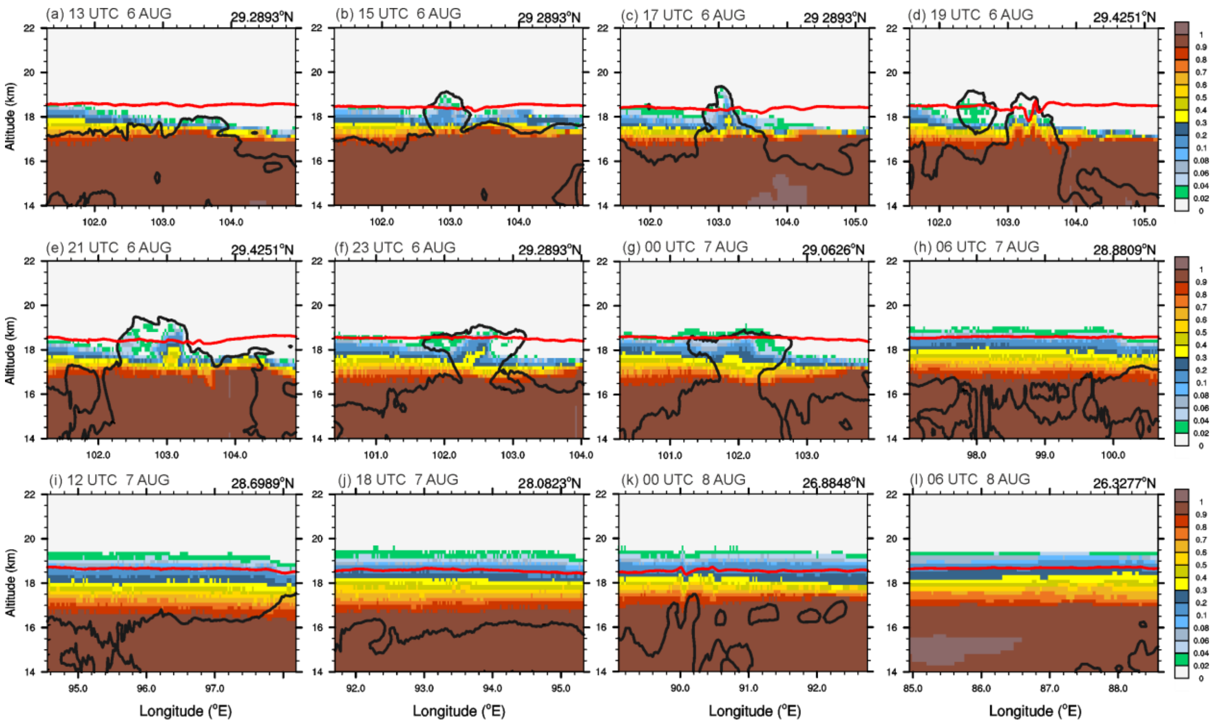

Figure 8. Same as Fig. 6 but for the tracer (%). The isentropic altitude of 410 K is depicted by the red line. The main changes of the tropospheric tracer by convective overshoots is marked by downward arrows.